Postprint: Characteristics of MSMA Sensors Under Multi-Parameter Variations

Authors: Lu Jun, Yu Qingyang, Su Chaofeng

Date: 2019-03-05T00:00:00+00:00

Abstract

Magnetically controlled shape memory alloy (MSMA) undergoes deformation under magnetic field; when external excitation force is applied, it induces changes in the material' s magnetic flux density, which subsequently manifests as variations in electrical signals. Based on this characteristic, this paper designs and fabricates an MSMA sensor prototype, constructs an experimental system, establishes an induced voltage model based on the variation of martensitic variant volume fraction, and investigates the output characteristics of the MSMA sensor under variations of multiple parameters including bias magnetic field, pre-pressure, and excitation force (amplitude and frequency). Through comparison between experimental and calculated values of the sensor, the universality and correctness of the sensor model under multiple parameter variations are verified, laying a theoretical and technical foundation for the application of MSMA sensors under complex conditions.

Full Text

Characteristics Study of Multi-Parameter Change of MSMA Sensor

Lu Jun, Yu Qingyang, Su Chaofeng
School of Automation and Electrical Engineering, Shenyang Ligong University, Shenyang 110159, China

Abstract: Magnetic controlled shape memory alloy (MSMA) produces deformation under the action of a magnetic field. When an external exciting force is applied, the magnetic flux density of the material itself changes, manifesting as an electrical signal variation. Based on these characteristics, this paper designs and fabricates an MSMA sensor prototype and constructs an experimental system. An induced voltage model is established based on changes in martensitic variant volume fraction, and the output characteristics of the MSMA sensor are studied under multi-parameter variations of bias magnetic field, pre-pressure, and exciting force (frequency and amplitude). By comparing experimental values with calculated values, the universality and validity of the sensor model under multi-parameter changes are verified, providing a theoretical and technological foundation for MSMA sensor applications under complex conditions.

Keywords: MSMA, sensor, multi-parameter, model, induced voltage

Funding: Supported by the National Natural Science Foundation of China (51377110) and the Open Fund of the Key Laboratory of Intelligent and Networked Measurement and Control Technology, Shenyang Ligong University (4771004kfs54).

---

1 Introduction

Magnetic controlled shape memory alloy (MSMA) is a novel functional material that exhibits magnetic field-induced or stress-induced martensitic reorientation at room temperature, with macroscopic strains reaching up to 10%. Ni MnGa is the most extensively studied MSMA, offering rapid response, high cost-effectiveness, and combined advantages of magnetostrictive and piezoelectric ceramics [1-5]. Depending on the type of martensitic variant reorientation, MSMA effects can be classified as either positive or inverse. The positive effect occurs when a magnetic field induces magnetically favorable variants, causing element elongation, after which the deformation recovers under mechanical force when the field is removed. The inverse effect occurs when, after deformation and under a bias magnetic field, mechanical force acts on the MSMA material, increasing stress-favorable variants while decreasing magnetically favorable variants, thereby altering the internal magnetic flux and manifesting as an electrical signal change [6]. While actuator applications based on the MSMA positive effect have been investigated, sensor applications utilizing the inverse effect have been rarely reported. Previous sensor models have mostly relied on empirical formulas for induced voltage, lacking universality [7-8]. Therefore, this paper aims to address practical application scenarios by examining voltage variations in the induction coil under complex external conditions, proposing a novel induced voltage model, and designing and fabricating an MSMA sensor. By comparing theoretical induced voltage values with experimental results, the variation patterns of sensor output and model adaptability under multiple parameter changes are verified.

---

2 Working Principle of MSMA Sensor

The working principle is illustrated in Figure 1 [Figure 1: see original paper]. Under pre-pressure F , the MSMA element has length l . When an exciting force is applied in the same direction as the pre-pressure, the element length further decreases to l , changing the internal magnetic flux and manifesting as an electrical signal variation. Upon removal of the exciting force, the element returns to length l .

The internal twin boundary changes in the MSMA material during this process are shown in Figure 2 [Figure 2: see original paper]. In Stage 1, stress-favorable variants constitute the main component with no significant twin boundary movement. Stage 2 consists of both stress-favorable and magnetically favorable variants, exhibiting a clear twin boundary. In Stage 3, stress-favorable variants continue to increase. In Figure 2, bold arrows indicate the combined action of exciting force and pre-pressure.

3 Sensor Experimental System

The sensor experimental system is shown in Figure 3 [Figure 3: see original paper]. The experiments utilize an MSMA element with dimensions of 2.5 mm × 5 mm × 20 mm, composed primarily of Ni MnGa. This paper develops a sensor prototype based on the MSMA inverse effect, consisting of an excitation coil, induction coil, movable push rod, baffle plate, spring, adjustment nut, and MSMA element. To restore the MSMA element deformation, an axial prepressure is applied via a spring. A signal generator produces a sinusoidal signal that is amplified and used as the input to a vibrator, which applies a varying force signal to the MSMA element. The voltage signal on the induction coil can be input to an oscilloscope, while force, Hall, and eddy current sensors detect the exciting force, magnetic flux density, and Ni MnGa element displacement, respectively.

Since axial force only generates an axial internal magnetic field, there is only one type of magnetocrystalline anisotropy energy, and the rotation of the magnetization vector is a reversible process. Kiefer and Lagoudas derived the expression for internal magnetization rotation as [10]:

$$\sin\theta_3 = \frac{\mu_0 M_s H}{2K_u}, \quad \theta_4 = 0$$

where H is the applied magnetic field strength and K is the magnetocrystalline anisotropy energy. Since the easy axis of magnetic domain 4 aligns with the external magnetic field, its magnetization rotation relative to the easy axis is zero.

4 MSMA Sensor Model

Under combined magnetic field and mechanical force, the total magnetization intensity of each single crystal is obtained by superimposing M and M . Microscopically, magnetic domains in each MSMA single crystal are randomly distributed, exhibiting magnetic anisotropy. The angle between the magnetization vector and the easy axis is called the magnetization rotation angle, denoted by . When a magnetic field is applied, the magnetization vector aligns with the field direction to minimize magnetic energy, causing the magnetization rotation angle to change, as illustrated in Figure 4 [Figure 4: see original paper].

Assuming each martensite variant contains two types of magnetic domains at room temperature, where 1- represents the volume fraction of the first type and represents the second type, the combination of two variants and two magnetic domains yields four distinct magnetization regions. Experiments show that even under small magnetic fields, one magnetic domain region disappears (because = 1), leaving only one type of magnetic domain region. It is assumed that is always 1 [9]. The magnetization rotation angles of the four magnetic domains are , , , and , with = . However, since only the second type of magnetic domain exists, only angles and (perpendicular to each other) appear in the material.

The relationship between M , M and M , M (magnetization vector components on the x and y axes) is:

$$\begin{pmatrix} M_x \\ M_y \end{pmatrix} = M_s \begin{pmatrix} \sin\theta_3 & \cos\theta_3 \\ \cos\theta_4 & \sin\theta_4 \end{pmatrix}$$

where M is the saturation magnetization of the magnetic domain, and M and M are the magnetization vector components on the x and y axes.

The total magnetization intensity of each single crystal under force and magnetic field is superimposed from M and M :

$$\bar{M} = (1-\xi)M_3 + \xi M_4$$

Substituting the expressions for M and M and assuming = 1 with only H field present:

$$\bar{M} = (1-\xi)M_s\sqrt{1-\left(\frac{\mu_0 M_s H}{2K_u}\right)^2} + \xi M_s$$

For small magnetic fields, this simplifies to:

$$\bar{M} = \xi M_s + (1-\xi)\frac{\mu_0 (M_s)^2 H}{2K_u}$$

where H is along the longitudinal axis (H_long = H) and the transverse field strength is zero (H_trans = 0).

The volume fraction   of different variants is given by [11]:

$$\xi = \frac{\cos\theta_3(\sigma - \varepsilon_m - b_1 - b_2 - CY) + 1}{2}$$

where   = F sin(t)/S_MSMA is the exciting stress on the element cross-section,   is the maximum axial strain of the element, S_MSMA is the cross-sectional area of the element, and b , b , C, and Y are constitutive model correction parameters that are constants.

Changes in variant volume fraction cause magnetization intensity changes, leading to time-varying magnetic flux density. According to Faraday’ s law of induction:

$$u = -NS\frac{dB}{dt}$$

where N is the number of coil turns, B is the magnetic flux density caused by sample magnetization, and S is the area of the element perpendicular to the magnetic field direction.

Substituting the expression for magnetic flux density into the induction equation yields the induced voltage expression under combined force and magnetic field:

$$u = R\varepsilon_m F_m f \sin\left(\frac{2\pi f_m F_m \sin(2\pi f t) - \mu_0 M_s H + b_1 - b_2 - CY}{C}\right)\cos(2\pi f)$$

The maximum strain   is related to the pre-pressure F by:

$$\varepsilon_m = 0.06 - 0.77\times10^{-2}F_0 + 0.52\times10^{-2}F_0^2 - 0.81\times10^{-3}F_0^3 + 0.39\times10^{-4}F_0^4$$

5 Experimental Results Analysis

The experiments use force and magnetic field parameters as variables, with constant parameters: M = 4.85 × 10 kA/m,   = 4 × 10   H/m, K = 1.56 × 10 J/m^3, S = 12.5 mm^2, N = 1500, C = 4.5, b = 1.956, b = 7.62, Y = 56.42. To verify model universality, multiple parameters are varied simultaneously to observe induced voltage patterns. Since pre-pressure rarely changes in practical applications, it is held constant (0.48 MPa) in all experiments, which are conducted at room temperature.

5.1 Induced Voltage Variation with Simultaneous Amplitude and Frequency Changes

With a constant bias magnetic field of 0.48 T, the amplitude and frequency of the exciting force are varied simultaneously. The calculated instantaneous induced voltage sensor output is shown in Figure 5 [Figure 5: see original paper]. The comparison between calculated and experimental peak-to-peak induced voltage values is shown in Figure 6 [Figure 6: see original paper].

Comparing test cases 3, 4, and 5 reveals that when both frequency and amplitude increase, the induced voltage increases. This occurs because higher frequency accelerates variant growth and disappearance, while increased amplitude enhances this effect. Comparing cases 5, 6, and 7 shows that despite frequency increases, the induced voltage still decreases, indicating that amplitude has a more pronounced effect on induced voltage than frequency.

5.2 Induced Voltage Variation with Simultaneous Amplitude and Bias Magnetic Field Changes

With the exciting force frequency held constant at 700 Hz, the amplitude and bias magnetic field are varied simultaneously. The calculated induced voltage is shown in Figure 7 [Figure 7: see original paper], with calculated and experimental peak-to-peak comparisons in Figure 8 [Figure 8: see original paper].

Comparing cases 3, 4, and 8 shows that when bias magnetic field increases while amplitude decreases, the induced voltage changes significantly despite relatively small variations in both parameters. This indicates that at smaller amplitudes and bias fields, the mechanical force effect is more pronounced than the magnetic field effect, as magnetization rotation initiation is more difficult than variant increase. Comparing cases 2 and 7 shows that even when both amplitude and bias field increase, the induced voltage increase is not obvious, because substantial changes in both force and magnetic field are required to produce significant magnetization angle rotation and new martensite formation, thereby generating larger induced voltage signals.

5.3 Induced Voltage Variation with Simultaneous Frequency and Bias Magnetic Field Changes

With the exciting force amplitude held constant at 1 N, the frequency and bias magnetic field magnitude are varied simultaneously. Model calculation results are shown in Figure 9 [Figure 9: see original paper], with calculated and experimental peak-to-peak comparisons in Figure 10 [Figure 10: see original paper].

Comparing cases 3 and 4 reveals that although the frequency is not the highest, the induced voltage is maximum, indicating that the bias magnetic field effect is more significant than frequency. Comparing cases 5 and 8, and 6 and 7, shows that when bias magnetic field increases while frequency decreases, the induced voltage increases multiplicatively despite only a 0.06 T increase in bias field. This demonstrates that the bias magnetic field has a more pronounced effect on induced voltage than frequency, because at higher bias fields, most martensite remains in the magnetically favorable variant state despite frequency changes, limiting the frequency effect.

6 Conclusion

Starting from microscopic martensitic variant volume fraction changes and magnetization rotation angle variations, this paper derives the induced voltage changes in MSMA under bias magnetic field and mechanical force, establishing a universal MSMA sensor model for complex conditions. Experiments conducted with the developed sensor prototype at constant pre-pressure show that: (1) experimental and calculated peak-to-peak induced voltage values are essentially consistent; (2) when amplitude and frequency are varied simultaneously, both are positively correlated with induced voltage, with amplitude having a greater influence; (3) at smaller exciting force amplitudes and bias magnetic fields, the amplitude effect is more pronounced, and both parameters require substantial changes to produce significant induced voltage signals; (4) when frequency and bias magnetic field are the variables, the bias magnetic field effect is more dominant.

References:

[1] Sozinov A, Likhachev A A, Ullakko K. Crystal structures and magnetic anisotropy properties of Ni MnGa martensitic phases with giant magnetic-field-induced strain[J]. IEEE Trans. Magn., 2002, 38(9).

[2] Zeng Jianbin, Bai Baodong, Zeng Gengxin, et al. Dynamic models of giant magnetostrictive ultrasonic transducer taking account into variable pressure[J]. Transactions of China Electrotechnical Society, 2012, 27(10): 215-219.

[3] Ullakko K, et al. Magnetically controlled shape memory alloys: a new class of actuator materials[J]. Journal of Materials Engineering and Performance, 1996, 15(3): 405-409.

Note: Figure translations are in progress. See original paper for figures.